N60530-5154
Galcit 105

ADDITIONAL EXPLORATORY PHOTOELASTIC STUDIES IN STRESS WAVE PROPAGATION

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This research was supported by the United States Navy Bureau of Ordnance, through the Naval Ordnance Test Station, China Lake, California, Dr. John Pearson, Project Engineer.

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5.2.13

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I. INTRODUCTION

In a previous report to the sponsor,** the design and description of a high speed framing camera was presented along with several film strips representing the results of a series of qualitative investigations of dynamic stress wave phenomena. These studies included crack propagation, layered media, compressed bars and beams, and cross sections of rocket heads.

As part of a continuing study in these and related fields, a final report is submitted covering (1) exploratory experimental studies of shock wave propagation initiated by explosive caps and by nitrogen shock wave impingement, and (2) theoretical studies of a series of dynamic stress wave problems carried out in conjunction with the overall problem.

II. EXPERIMENTAL STUDIES

The high speed camera shown in Figure 1 has been used to record shock wave phenomena in two solids using two different means of loading initiation. In the first a primer cap was placed at the center of an edge of a 1/4 inch thick piece of CR-39 containing a central hole. A film clip of the initiation and early stages of the

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**Williams, M. L., Jessey, M. E., Parmerter, R. R.: Some Exploratory Photoelastic Studies in Stress Wave Propagation. Report N123-60530S-3825a: T.O. 1 (Galcit 90), Guggenheim Aeronautical Laboratory, California Institute of Technology, October, 1958.

propagation is shown in Figure 2 which was recorded at 100,000 frames per second and 0.093 microsecond exposure. The main feature to observe is the distinction between this fringe pattern which clearly exhibits the hemispherical shock wave, and the characteristic Boussinesq pattern which would normally be expected by a static or pseudo-static loading, such as seen under the impact load in Figure 15 of the previous stress wave report.*

These data compare quite favorably with those recorded by Feder** et al and demonstrate the refraction around the circular inclusion. Even at this comparatively slow framing rate, approximately eight frames were recorded before reflection at the edges of the specimen. One should also observe that behind the shock wave the pseudo-static Boussinesq fringes occur and continue to build up in strength until about the tenth frame when the peak force of the cap has been reached. Subsequently the total force is seen to reduce. Some rough calculations indicate that the impulse generated by the cap is of the order of 600 pound-microseconds.

The second and most recent shock wave experiment consisted of the use of an aerodynamic shock tube to load a low-modulus photoelastic material in a dynamic manner. A rectangular 1/2 inch x 1 inch shock tube (shown in Figure 3) was built to be used in conjunction with the high speed framing camera and its associated light source and controls. The driving fluid was compressed nitrogen gas.

The specimen, a 12 inch square slab of 1/2 inch thick Hysol 8705 urethane rubber compound, was mounted at the end of the shock tube in a plane perpendicular to the light path. It was enclosed in a model holder consisting of plexiglass plates on the two faces and another plate on the top, as indicated at the left in Figure 3, leaving

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*Ibid.

**Feder, J. C., Gibbons, R. A., Gilbert, J. T., and Offenbacher, E. L.: The Study of the Propagation of Stress Waves by Photoelasticity. Proc. of the Society for Experimental Stress Analysis, vol. 14, n. 1, 1956, pp. 109-117.

therefore an enclosed rectangular space above the specimen through which the nitrogen shock passed.

In operation, one or more diaphragms of Mylar plastic are inserted between a pair of flanges about halfway along the tube. With increasing pressure from the nitrogen gas source, the diaphragm bursts, resulting in the formation of a shock wave that travels down the tube, passes over the upper surface of the model, and exhausts into air at atmospheric pressure.

Also shown attached to the shock tube in Figure 3 are the two high frequency electrical leads sending the signal of the passing shock wave from two resistance thermometer type pick-ups (located 10" apart near the exhaust end of the tube) to an amplifier and Berkeley 7360 microsecond counter. A thin and narrow platinum film sputtered onto the glass pick-up body acts as an electrical conductor of small inertia whose resistance varies with temperature; the amplifier boosts this signal generated by the temperature jump existing across a passing shock wave. The amplified pulse actuates the counter to give shock speed and, after suitable time delays, also fires the light source and initiates the Kerr cell shuttering action. The manufacture and operation of these pick-ups has been described by Rabinowicz,* et al.

The photoelastic bench was modified to incorporate the complete set of 10" diameter lenses, polaroids, and quarter wave plates so that a large photoelastic field could be maintained and approximately parallel light passed through the model. Auxiliary lenses were used to help diffuse the light from the flashtube and condense the light beam to pass it through the Kerr cell and camera lens.

The model material used was Hysol 8705, a urethane rubber compound of quite low elastic modulus (less than 1000 psi). This characteristic guarantees that the shock wave travels over the model faster than the stress waves propagate in the material; hence the disturbance in the model cannot get ahead of the actuating pressure pulse

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*Rabinowicz, J., Jessey, M. E., and Bartsch, C. A.: Resistance Thermometer for Heat Transfer Measurement in a Shock Tube. Galcit Hypersonic Research Project, Memorandum No. 33, July 2, 1956.

of the shock wave. Hysol is more translucent than transparent, which at one and the same time provides the diffusion necessary to eliminate striations resulting from the coiled flashtube geometry, but also seriously reduces the amount of light transmitted and hence lessens the sharpness of the stress fringes. The best currently available 35 mm film fast enough to give usuable pictures under these conditions is Agfa Isopan Record film with a nominal ASA rating of 640. Improvements in optics and light source to increase the film density are planned.

A typical result from one of the earlier shots is shown in Figure 4 which was recorded at 84,600 frames per second and 0.093 microsecond exposure. The nitrogen shock wave was set off with a reservoir pressure of 750 psi at 75° F and just prior to entering the test section over the Hysol specimen was traveling at 2360 feet per second as measured by the platinum film pickups. The time represented by the 20 frames shown is about 240 microseconds immediately after the shock wave has started moving across the surface of the model. (The film frame numbers advance in the direction of increasing time, but the images appear approximately inverted so that the shock wave is traveling from right to left through the light rectangular area near the bottom of each frame; the model material displays the photoelastic fringe and darkened quarter-circle patterns as the shock wave advances.)

The film clip very clearly shows the shock wave coming upon the specimen and progressing across it at essentially no decrease in velocity. Two interesting features of the step are currently under study: first, the curvature of the wave front, and second, the overlay circular wave emanating from the corner which may be due to an air shock in the slight clearance between the specimen and its enclosing plexiglass face plate.

In addition to the above experimental studies, an extensive amount of time was spent in equipment modification. Aside from the shock tube described above, the possibility of placing a microscope in the light path, without polaroids and quarter plates, to make microkinetic photographs has been under investigation. This has proven possible under a combined effort sponsored jointly by the

U.S. Naval Ordnance Test Station and the Aeronautical Research Laboratory, Wright Aeronautical Development Center.* The significant finding that has come out of this work is that the film density can be considerably improved without loss of resolution. The reason for this is that there are a number of settings possible for any given magnification contraction of the image, but only one of them has maximum light intensity. Procedurally, a small photocell coupled with a meter can be used very effectively to optimize the lighting conditions before any pictures are taken.

Since the optimization of lighting was investigated under conditions of linear magnification of an object in the range of 5 to 25, the focusing was very much dependent upon the precision of settings. Hence, a new optical bench was built during this study which offers precisely controlled movement of the various elements mounted on it.

For focusing purposes a slightly modified light source was used. A Sylvania concentrated arc point source lamp (C2P) was mounted on the same type of socket as the G.E. flash tube used for pictures under dynamic conditions, and this arc was located so that its source was in the same plane as the front surface of the flash tube. Focusing could be done with the point source light. This light was then replaced by the G.E. flash tube, thus assuring oneself that the focusing was correct. This principle was tried out over a range of magnifications from 5 to 25 and found to be successful. It has, however, not yet been tried out for a contracting field. It is apparent that for a contracting field this is not as serious a problem as it is for a magnifying field.

As was mentioned above, a distinct improvement in technique consisted of using a small photocell to measure the light intensity off the ground glass focusing screen before taking any pictures. It was found possible by this method to predict in a sufficiently

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* Cf. Valluri, S. R.: Kinetics of Deformation and Fracture. Galcit 107 (Contract No. AF 33(616)-6270) Progress Reports No. 1 (April 15, 1959) and No. 2 (July 15, 1959). Guggenheim Aeronautical Laboratory, California Institute of Technology.

accurate manner the quality of the picture one could obtain. Ordinary light meters were inadequate for this purpose since the light intensities in this work were too small.

Two other improvements that were tried during this period were (1) various other films, and (2) prefogging techniques. It was found that Agfa Isopan Record film with nominal ASA speed of 640 and usable up to 8000 was much better than all the other films tried so far and specifically better than Kodak Tri-X. Prefogging was also tried out on this film before the actual pictures were taken and it was found that there was an optimum prefogging condition which would increase the film density by about two to three times.

Figures 5 and 6 are self-explanatory, illustrating that a certain amount of success has been achieved in recording high speed pictures at approximately 6000 area magnifications.

III. THEORETICAL STUDIES

The test program has been carried out in parallel with analytical studies of various problems which are related to the experiments. Inasmuch as separate copies of these problems have been transmitted to the Project Engineer, they are simply itemized herein with a short summary accompanying each topic:

1. D. D. Ang: Transient Motion of A Line Load on the Surface of an Elastic Half-Space. The paper investigates the wave patterns generated by a line load moving on the surface of an elastic half-space with a velocity varying as a step function of the time. The complete range of velocities from zero to infinity is investigated. The fundamental differences among the "subsonic," "transonic," and "supersonic" regimes* of motion of the load are stressed. An interesting feature is the "resonance" effect due to the motion of a load at a velocity close to the Rayleigh wave velocity.

The solution given in closed form is obtained by the method of Fourier integral equations.

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* A "transonic" regime corresponds to a case in which the velocity of the load lies between the two velocities of sound in the material, and similarly for "subsonic" and "supersonic."

2. D. D. Ang: Elastic Waves Generated By A Force Moving Along A Crack. An investigation is made into the wave patterns generated by a line load moving along a half-plane crack in an infinite elastic solid with a velocity varying as a step function of the time. The stress "singularities" at the edge of the crack are investigated. The resonance effect associated with a motion at a velocity close to the Rayleigh wave velocity is noted. Because of this resonance effect, the Rayleigh wave velocity is, in the author's opinion, a possible value of the limiting velocity of propagation of a crack; for as can be seen easily, the propagation of a crack is a phenomenon caused by a force of such a magnitude and moving with such a velocity that it exactly cancels the surface stresses originally induced on the surfaces swept by the moving force.

The solution is obtained by the method of Wiener-Hopf integral equations.

3. D. D. Ang and M. L. Williams: Dynamic Stress Field Due to a Normal Dislocation. The paper investigates the dynamic stress field generated by a plane extensional dislocation* of constant strength in an infinite elastic solid moving with a velocity varying as a step function of the time. The complete range of velocities from zero to infinity is investigated. The stress singularities at the edge of the dislocation are found to be of the order r^{-1} where r is the distance from the edge.

The solution given in closed form is obtained by the method of Fourier integral equations.

4. D. D. Ang: Dynamic Stress Field Due to the Instantaneous Opening of a Half-plane Crack. The paper studies the wave patterns generated by the sudden opening of a half-plane crack in an infinite elastic medium initially subjected to a uniform tensile stress in the direction perpendicular to the plane of the

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*By a normal "dislocation" is meant a discontinuity in the displacement normal to the direction of propagation.

crack. While this problem was solved earlier by A. W. Maue using the method of conical flow, it is solved here by the method of Wiener-Hopf integral equations (in fact its solution follows immediately from the results of the paper "Elastic Waves Generated by a Force Moving Along a Crack" listed above). The author's excuse for taking up this problem is that it is wished to find a first order correction to the stress singularities in the neighborhood of the edge of the crack exhibited in Maue's solution.

IV. CONCLUSION

Joint experimental and theoretical research in this subject area is being continued with the U.S. Naval Ordnance Test Station under a new contract.

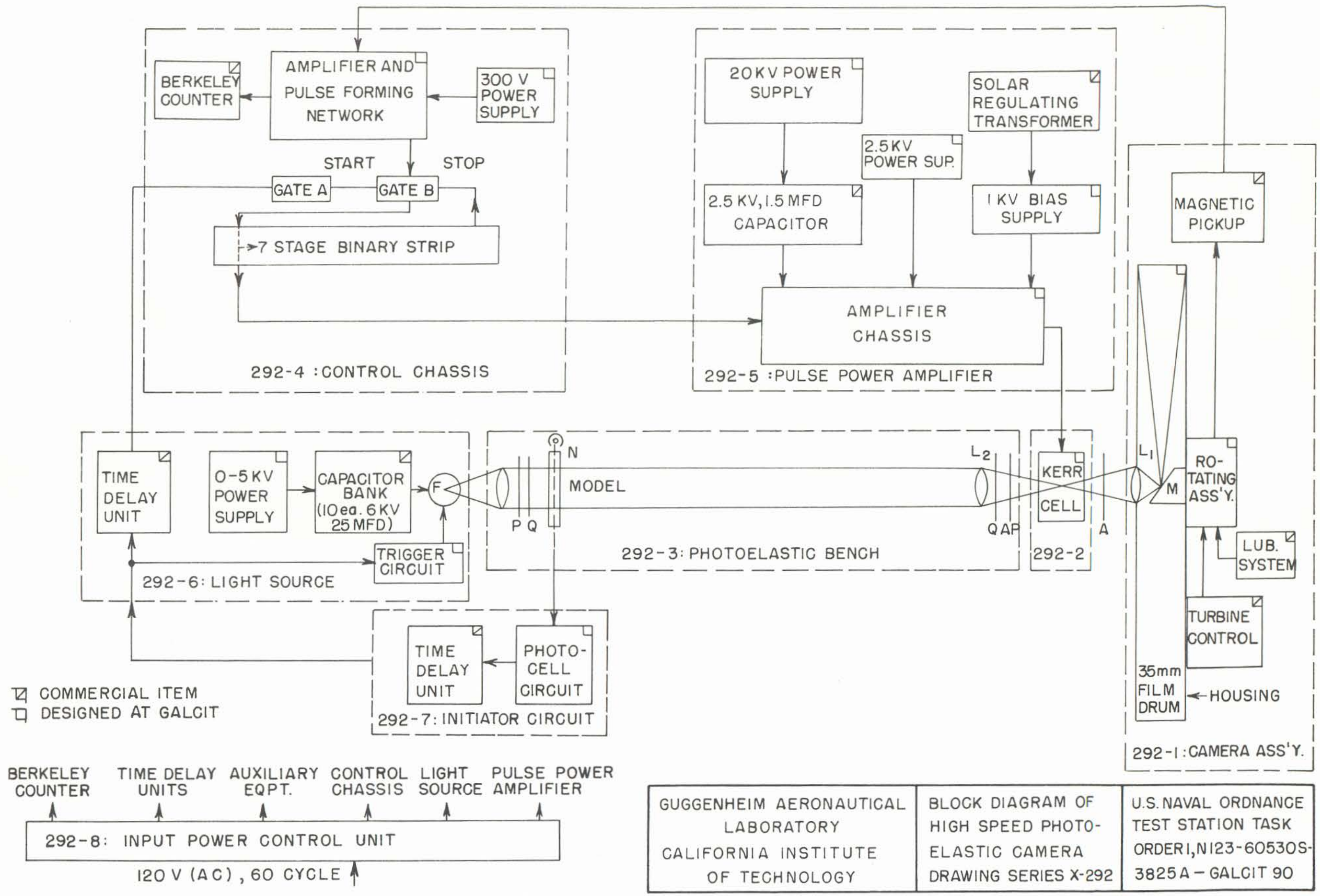
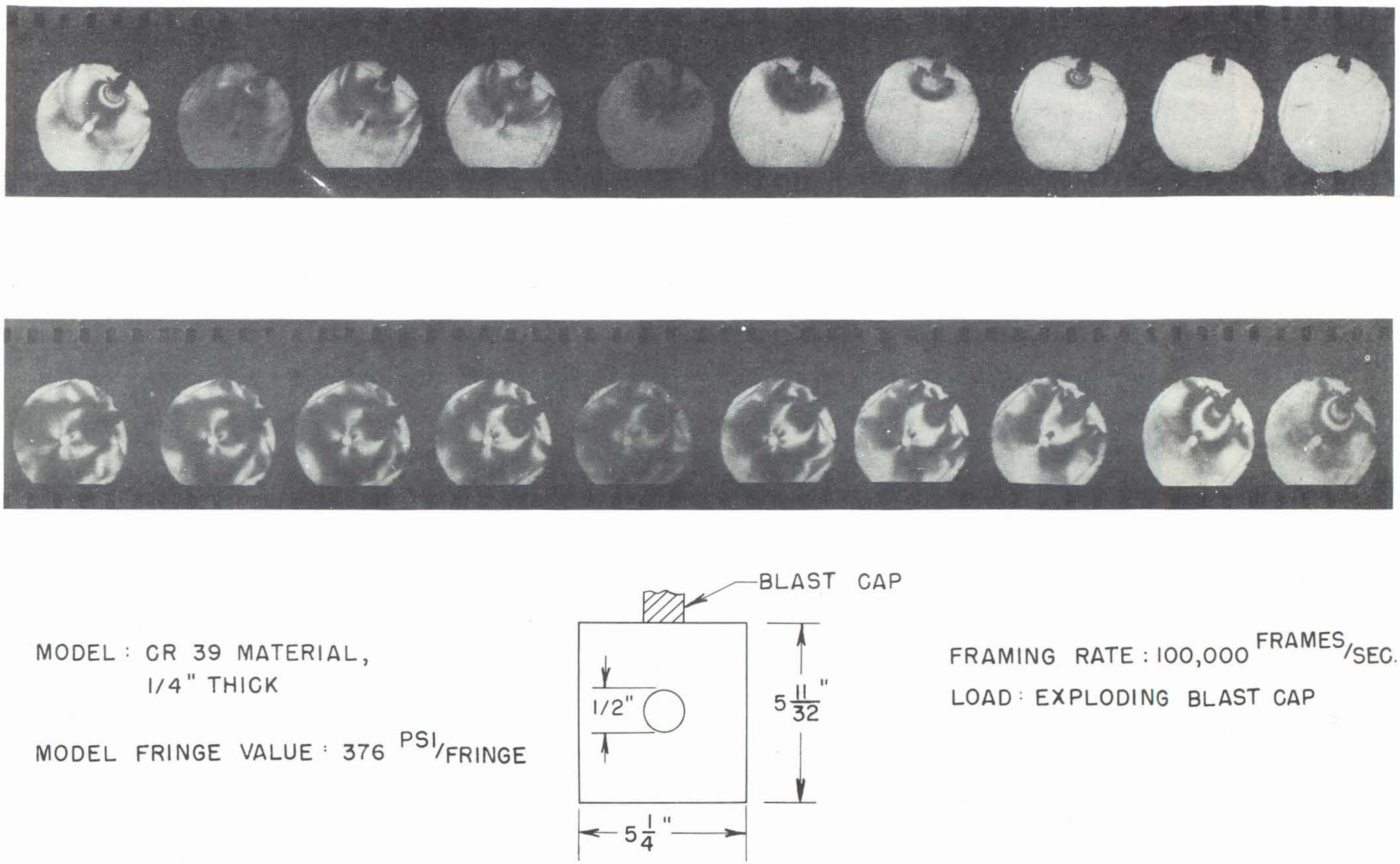


Figure 1. Block Diagram of High Speed Photoelastic Camera Drawing

Series X-292.



MODEL : CR 39 MATERIAL, 1/4" THICK

MODEL FRINGE VALUE : 376 PSI/FRINGE

FRAMING RATE : 100,000 FRAMES/SEC.

LOAD : EXPLODING BLAST CAP

FIG. 2 - DYNAMIC STRESS DISTRIBUTION FROM EXPLOSIVE LOAD IN A RECTANGULAR MODEL CONTAINING A HOLE.

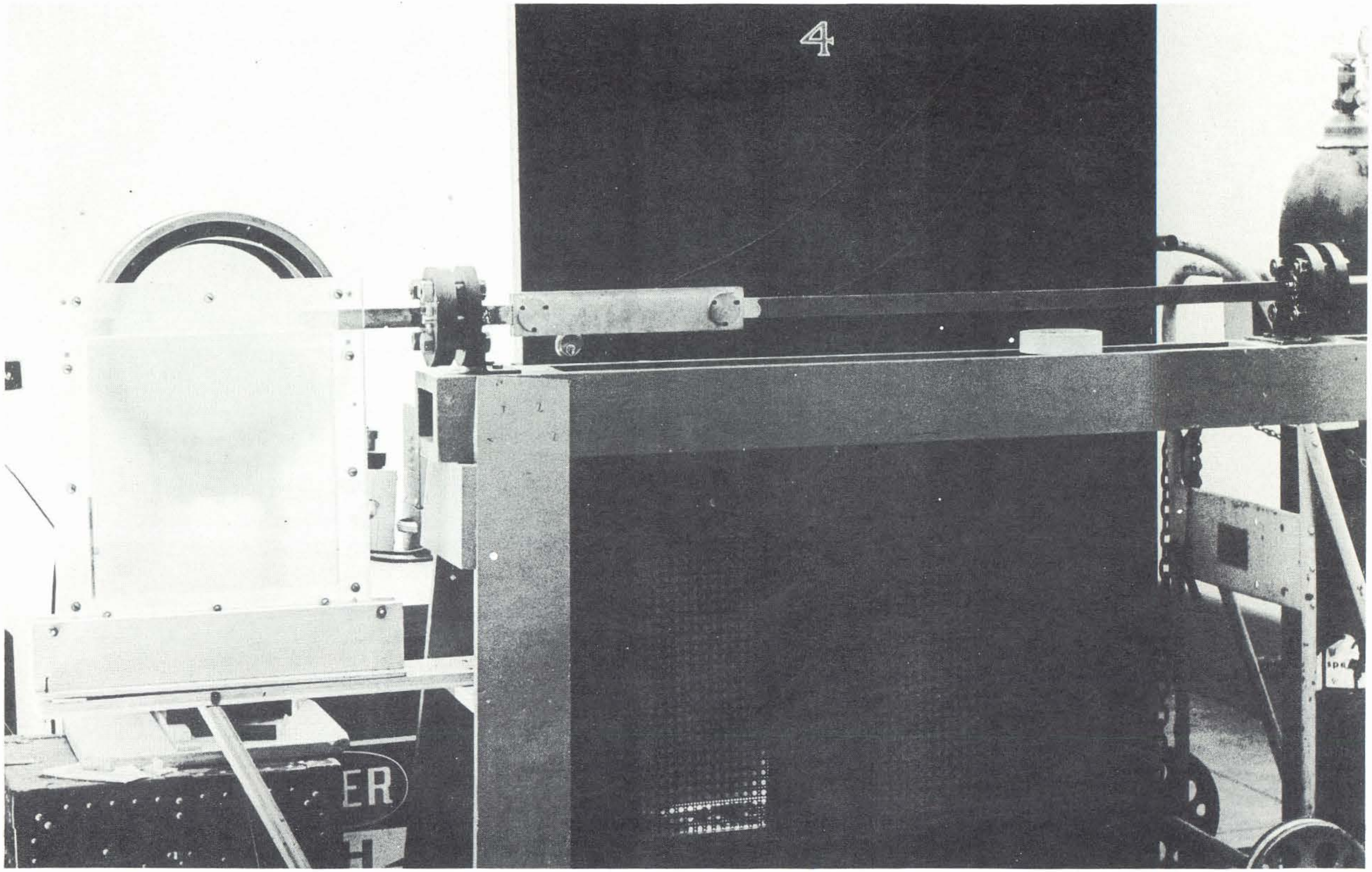
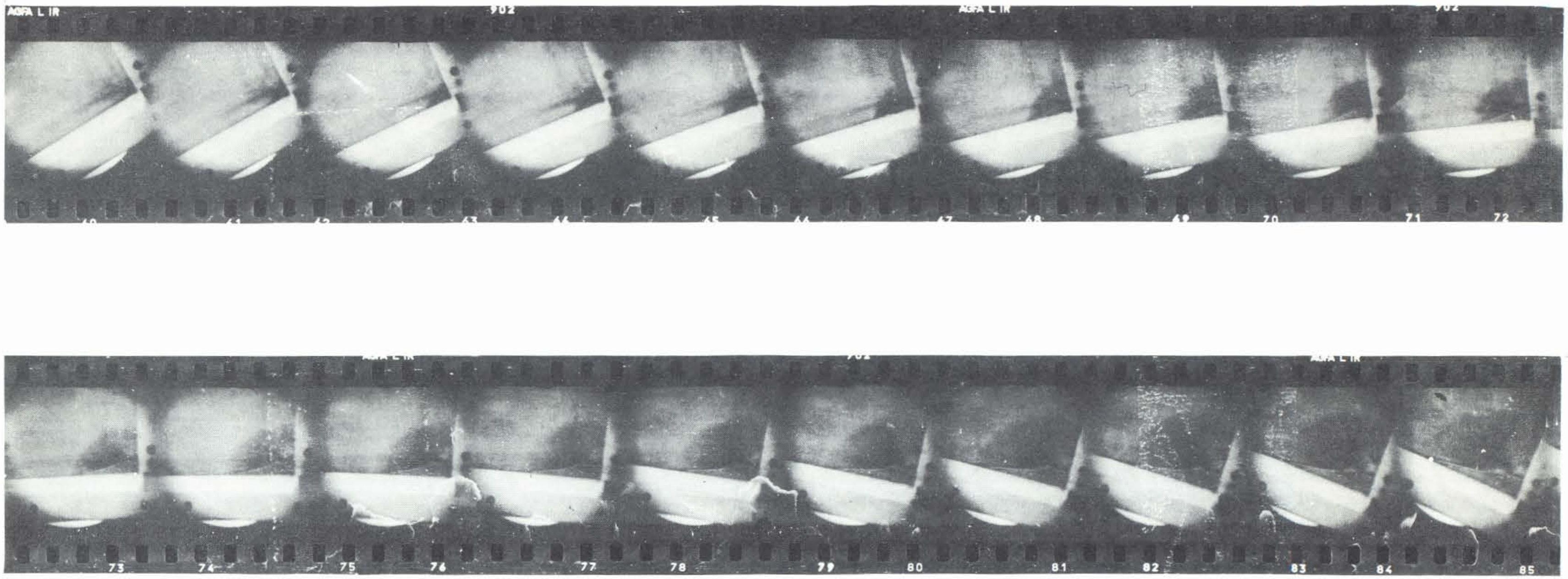


Fig. 3. Shock tube with resistance thermometer pickups and model holder (left) containing rectangular Hysol model.



Model: Hysol 8705 urethane rubber compound, 1/2" thick.

Framing rate: 84, 600 frames/sec.
Polariscope: Light field.

Fig. 4. Dynamic stress distribution from shock wave passing over rectangular models.

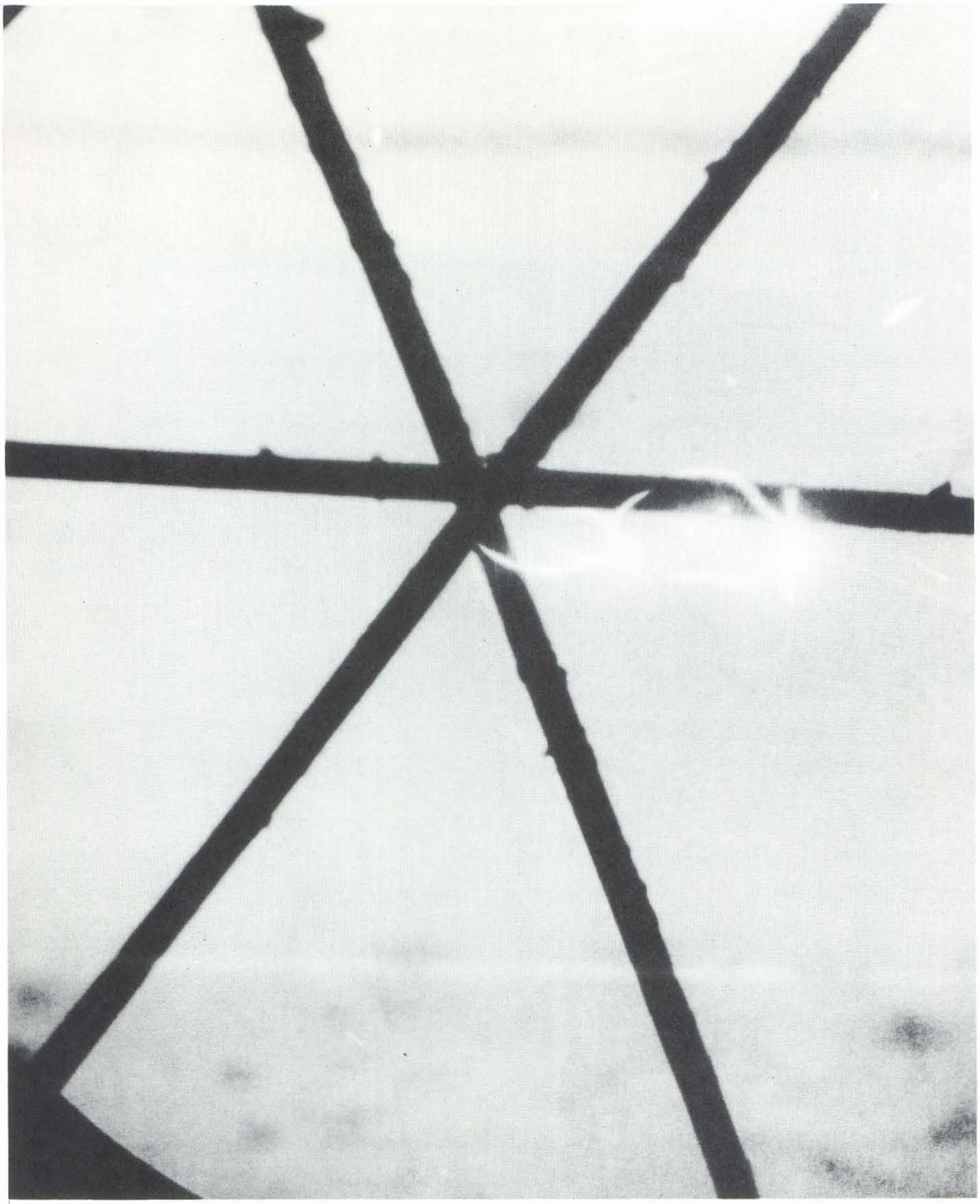


Fig. 5. Static picture of the .003 inches diameter cross wires using point source light. Direct magnification 8.5 linear. Total magnification 80 linear. Tri-x film with extended development technique.

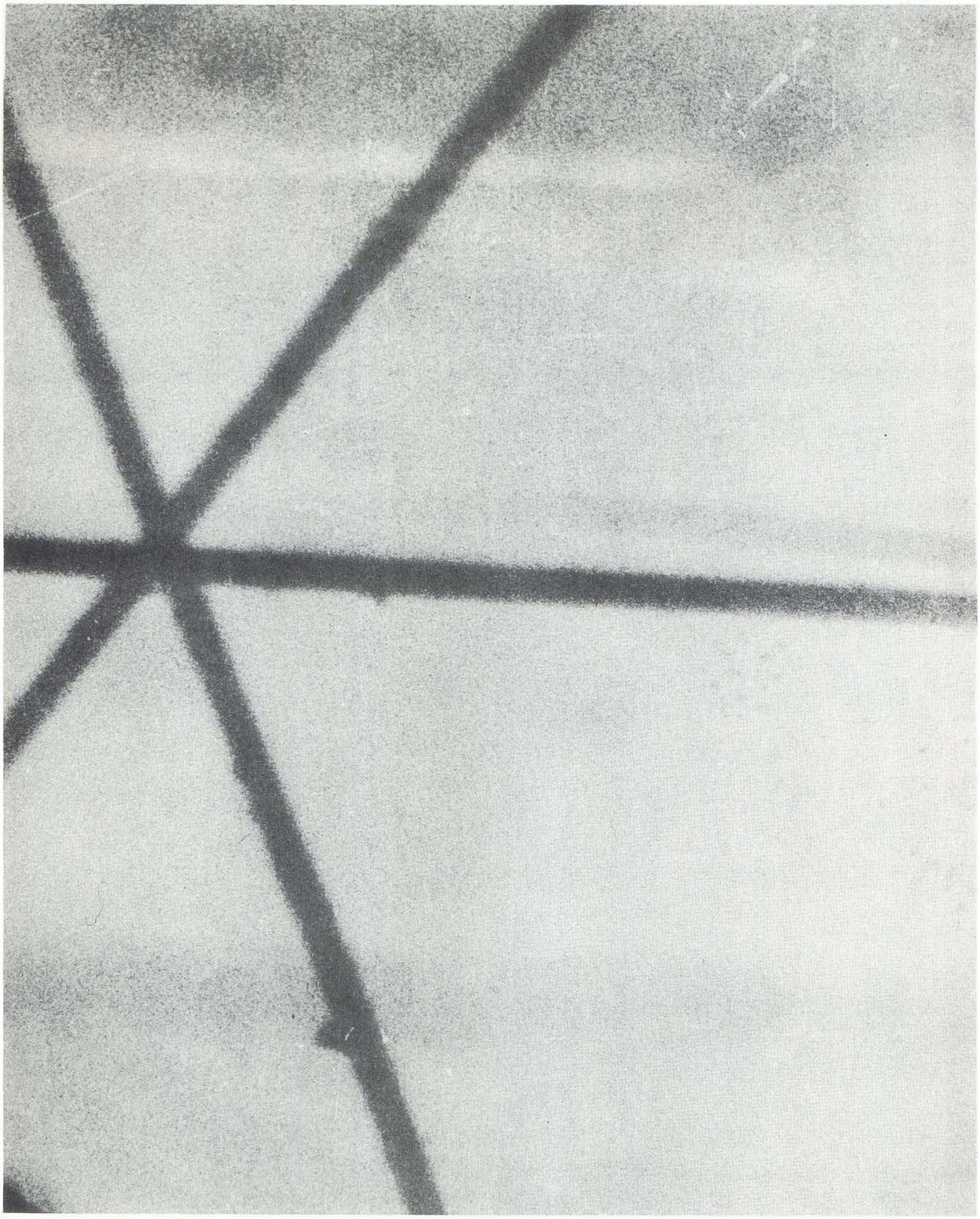


Fig. 6. Dynamic flash picture of the .003 inches diameter cross wires. Framing speed: 70, 000 per sec. Exposure time 1/10th microsecond. Direct magnification 8.5 linear. Total magnification 80 linear. Compare with Figure 5. Tri-x film with extended development technique.